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System for automated fatigue crack growth testing under random loading

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Procedures have been developed for computer-controlled crack propagation testing under random load sequences. They include certain features which are not available in conventional systems, but which appear essential for random load testing. These include the capability to simulate any desired K-function on standard laboratory specimens and continuous on-line rainflow analysis of the test load sequence to exclude cycles falling below given values of threshold stress intensity, stress level or range. The system also includes a procedure for automated crack-opening displacement based crack opening/closing load level measurement. Experimental studies on Al-Cu alloy sheet material point to a requirement for development of standards for spectrum loading crack growth testing.

Key words: fatigue; fatigue crack propagation; automated testing; random loading; cycle counting

Terminology

Characteristic K	K associated with a stress characteristic of a given load spectrum. Can be mean, maximum, RMS, *etc.*
Mean stress intensity, K_m	K associated with non-overload condition. For aircraft, K due to Ig stress (level flight).
Threshold K	K-range below which crack growth rate is negligible. Also refers to user defined K-range, cycles below which are excluded from the test.
Truncation levels	Upper and lower bounds of g in the spectrum. Values beyond this range are truncated to the assigned bounds.

Service loads on most engineering structures and many machine components are random in nature. Such sequences induce a number of load interaction effects which make it extremely difficult to extrapolate constant amplitude fatigue crack propagation (FCP) data to conditions of variable amplitude loading. Wherever possible, the performance of candidate materials should therefore be evaluated under conditions representative of actual service environment. Servohydraulic fatigue testing machines have gone a long way in making such studies possible. Standard load spectra have been developed to represent specific loading conditions; the FALSTAFF spectrum' is a typical example.

Procedures for constant amplitude FCP testing assume a unique relationship between crack growth rate, $daldN$, and effective stress intensity range. Reference 2 describes standards for such tests. However, da/dN under spectrum loading is not a function of a characteristic K alone. It has been shown that at identical mean stress intensity, K_m under spectrum loading, $daldN$ is strongly affected by mean stress, S_m. A recent study showed that dK/da and, to some extent, even net stress can affect the FCP process under spectrum loading.[4] It follows that laboratory data obtained on a particular crack geometry or stress level cannot always be extrapolated to situations of practical interest. This observation points to a new requirement for FCP testing under random loading - the capability to simulate on standard specimens any desired variation of characteristic K with crack length. This would permit generation of more meaningful test results for service load spectrum loading using standard laboratory specimens.

In most service load spectra, the logarithm of the frequency of occurrence of different loads is inversely proportional to their magnitude. Crack extension under such loading occurs predominantly under the larger load cycles. The load omission range is therefore an extremely critical parameter.[5] A smaller omission range may indefinitely extend test duration without affecting test results. A larger omission level may noticeably reduce the severity of the spectrum thereby leading to unconservative life estimates. In principle, the omission level should be related to the threshold stress intensity and therefore to the current crack length. The omission level therefore ought to change not only from material to material but also with crack length in a single test.

Conventional FCP test procedures were developed mainly for constant amplitude loading. In order to fulfill the two additional requirements described above, procedures were recently developed at the National Aeronautical Laboratory (NAL) for fully automated FCP testing under random load sequences. They permit stress- and K-controlled testing under any given load sequence including constant amplitude, programmed block, arbitrary peak/trough and Markov-matrix based random loading. This paper describes features of test software and hardware developed for random load testing with K-control, crack length and crack opening/closing load measurement and on-line modification of test load sequence through rainflow analysis.

The test system consists of a 25-ton Instron servo-hydraulic testing machine linked to a 56 kbyte PDP 11/23 computer operating on the Instron time-sharing operating system. Reference 6 describes the system hardware and the software developed at NAL to enable batch processing of FCP test jobs on multiple test systems.

Load spectrum representation

The load spectrum is stored as a Markov matrix representing the frequency of occurrence of various load excursions over a specified period of service. This format has been found to be the most suitable for a variety of load spectra including aircraft' and automobiles? Of the various available formats for load spectrum representation, the Markov matrix permits a more faithful reconstruction of service load history.

The matrix shown in Table 1 was derived from flight data records of a combat aircraft. Each element in the matrix represents the frequency of occurrence of a load excursion from the g-level shown in a particular row to the one in the corresponding column.

Prior to commencement of a test, the computer accesses the required disc-based data file containing information on the load spectrum. A generalized spectrum data format was evolved to enable implementation of a variety of load spectra. Spectrum definition is through: 1) array of load levels, 2) Markov matrix of load excursion frequency, and 3) spectrum constants.

The array of load levels contains load levels associated with individual rows in the Markov matrix. These cover the entire range of loads in the spectrum and are usually (though not necessarily) evenly spaced (0.5g in case of the spectrum in Table 1). The spectrum constants include:

- Markov matrix size (limited by computer memory), usually in the range 16 x 16 to 32 x 32
- total number of blocks/flights representing service life covered by matrix
- block/flight duration in number of cycles. This value is constant and equal to average duration. It is assumed that this simplification will not seriously affect test results
- baseline (mean/design) load level (lg load level for aircraft)
- end-of-block load level to be applied after each block (ground-air-ground cycle for aircraft)
- matrix entry point load level. That this should be the same as the first registered load level during spectrum derivation is an important requirement. Non-compliance can lead to residual excursions (particularly of large magnitude) in the matrix which cannot be generated for want of an entry point
- frequency scaling factor. This (optional) constant will be used to scale frequency down with increase in load range to permit optimum machine performance, particularly with low capacity powerpacks
- spectrum maximum and minimum load truncation level, threshold stress intensity of the material to be tested, lowest possible crack opening stress level and load omission range. These parameters control the process of on-line rainflow fatigue cycle analysis during the test.

Mean load control

The FCP test control job consists of three timesharing tasks:[6]

1) the FCP test controller which controls the overall sequence of testing
2) the load generator which generates the required load sequence for the test
3) virtual machine processor, which provides the software interface to drive the testing machine.

The load generator generates load levels from the Markov matrix. These are fed by the virtual machine processor into a hardware segment generator which generates the required waveform of the load control signal. In conventional systems, this signal is fed directly into the control loop of the testing machine. A minor modification was carried out to this scheme to permit K-controlled testing. This is shown in Fig. 1. In this circuit, the demand signal is scaled down through multiplication by a constant voltage signal deposited through a digital-to-

Table 1. Markov matrix of 9-load spectrum for a combat aircraft (covers 533 flights)

g	-2.5	‾2.0	-1.5	-1.0	-0.5	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0
‾2.5	0	2	0	1	0	0	0	3	6	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0
‾2.0	2	0	1	0	0	1	1	27	24	13	6	3	9	3	1	1	1	0	2	0	0	0	0	0
-1.5	0	1	0	1	3	0	2	39	31	9	6	11	6	3	1	2	2	0	1	0	2	0	0	0
‾1.0	0	1	1	0	2	2	2	22	23	14	2	0	0	1	1	0	0	0	0	0	0	0	0	0
‾0.5	0	0	3	2	0	8	19	39	45	17	8	6	2	6	2	3	2	0	0	1	0	0	0	0
0.0	0	1	1	2	7	0	60	472	332	122	63	55	22	27	21	13	13	5	5	4	3	1	1	1
0.5	0	2	1	2	22	57	0	2410	3408	1125	585	391	268	179	121	95	63	60	29	19	7	6	5	0
1.0	6	37	44	18	44	461	2402	0	1773	1398	580	312	196	120	79	52	27	19	12	9	5	0	2	0
1.5	4	11	23	19	35	322	3487	1741	0	564	529	207	74	34	12	6	8	2	2	1	0	1	0	0
2.0	1	18	9	16	19	144	1183	1363	511	0	336	324	116	35	19	10	2	3	1	0	1	0	0	0
2.5	0	7	4	4	6	83	594	590	531	296	0	196	194	55	28	11	3	4	0	0	1	1	0	0
3.0	0	2	13	2	9	57	357	334	197	339	195	0	140	118	44	15	4	3	1	1	0	0	0	0
3.5	0	9	9	1	8	32	260	206	90	126	184	125	0	75	76	23	6	1	4	1	0	0	0	0
4.0	2	1	3	0	5	26	167	104	47	44	63	126	68	0	43	44	9	5	2	1	2	0	0	0
4.5	0	1	2	1	0	17	111	89	25	17	33	45	70	37	0	26	23	7	1	0	0	0	0	0
5.0	0	1	3	1	3	13	72	61	17	12	9	18	30	44	17	0	8	11	5	1	0	0	0	0
5.5	0	0	4	0	0	5	53	35	9	4	3	3	9	16	21	9	0	3	5	3	0	1	0	0
6.0	0	0	0	0	0	14	30	24	9	6	5	3	5	4	10	9	4	0	0	3	0	0	0	0
6.5	0	1	0	0	0	3	24	21	2	0	0	0	2	2	5	4	5	1	0	2	2	0	0	0
7.0	0	0	0	1	0	3	15	5	0	3	1	4	1	2	2	2	3	2	2	0	2	0	0	0
7.5	0	0	0	0	0	3	7	4	2	0	0	2	0	1	1	1	0	0	2	2	0	0	0	0
8.0	0	0	0	0	0	2	5	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
8.5	0	0	0	0	0	0	4	3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
9.0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

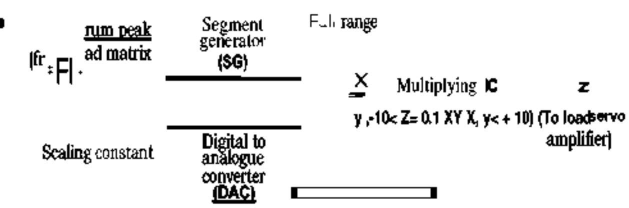

Fig. 1 Schematic of load signal generation circuit. The SG is controlled by the spectrum load generator task, the DAC is controlled by the FCP test controller to set mean stress

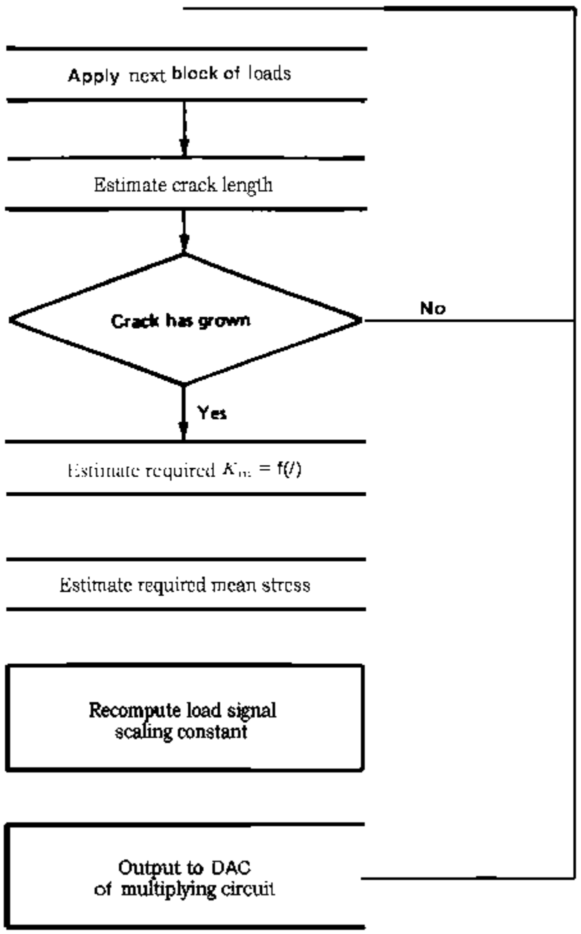

Fig. 2 Readjustment of load scaling factor in K-controlled testing

analogue converter (DAC) by the FCP test controller. The DAC in effect acts as a computer-controlled potentiometer on the control signal line.

In a mean-stress controlled test, the scaling factor is computed only once at the commencement of the test. In a K-controlled test, the scaling factor is recomputed each time an increment in crack length is registered (but not more than once every flight). The flow-chart for this procedure appears in Fig. 2. By reducing CPU overheads, the multiplying circuit appears to be vital for K-controlled random load testing. The analogue-multiplying integrated circuit functions by generating the antilog of the sum of logs of two signal values. This principle introduces certain error. It would be more appropriate to use a multiplying DAC instead.

It must be noted that spectrum load levels are non-dimensionalized. Most FCP tests are carried out under elastic nominal stresses. Therefore stresses associated with *individual* load levels are obtained by multiplying each level by a predetermined constant set as one of the inputs of the multiplying circuit.

The hardware segment generator takes values from the non-dimensionalized load level array. These levels are selected to ensure waveform generation over its entire range, thus providing for better load signal resolution even at low spectrum mean loads.

Crack length measurement

Automated FCP testing requires instrumentation for crack length measurement. These measurements should be reasonably accurate and in no way affect the FCP process itself. The crack-opening displacement (COD) compliance,[8] AC' and DC[10] potential drop techniques have been widely used for crack length estimates. The compliance technique has hitherto been used mainly on compact-tension (CT) specimens with a standard COD clip gauge. A COD gauge was developed for use on single-edge notch-tension (SENT) specimens cut from thin sheet material (1 to 6 mm thickness). A schematic of the gauge appears in Fig. 3. It uses a single cantilever sensitive element deflected by the tip of the screw mounted on the lower block. The gauge in effect measures displacement at a point about 7 mm from the specimen edge.

The crack length - COD compliance function is experimentally determined for the specimen geometry of interest. It is represented as a fourth order polynomial. During the automated test, crack length is computed from unloading compliance during a specially introduced ramp down to 75% of current load. It is assumed that crack closure is absent at such loads. During unloading, load and COD outputs are sampled every 10 ms. A machine code routine fits a straight line through the sampled points. The slope of this line gives compliance. To avoid possible errors due to noise, *etc,* compliance measurements are repeated. Crack increment is registered only when consistent increase in compliance is observed (see Fig. 4). The resolution of the technique was found to be better than 0.1 mm. As the additional load cycles introduced for crack length measurements are small, their contribution

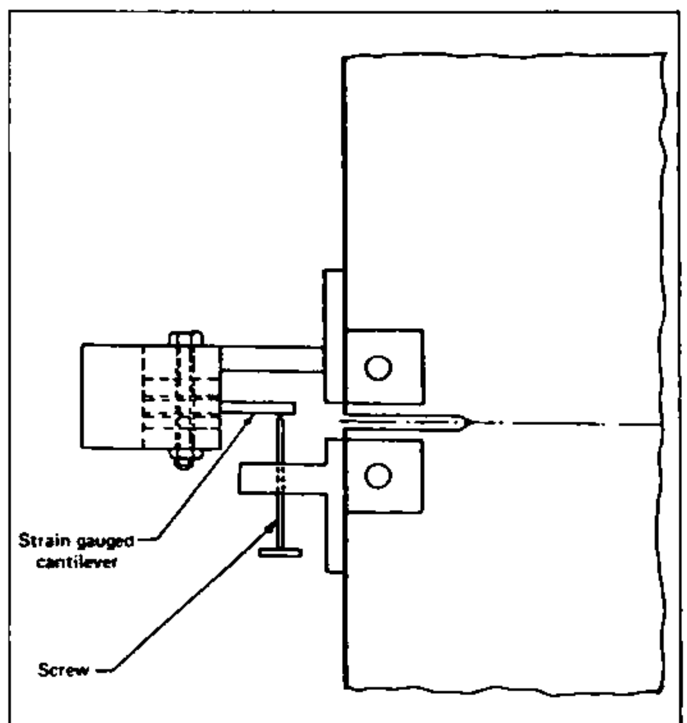

Fig. 3 Schematic of COD gauge for SENT specimens

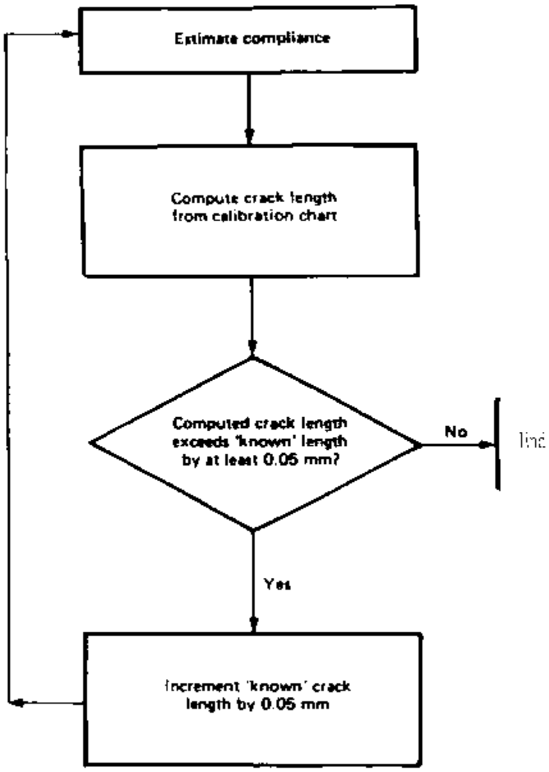

Fig. 4 Flow-chart for the crack length measurement

to the FCP process is ignored. It may be noted that this procedure for crack length measurement can be easily adapted to other types of COD gauge. As the crack length measurement is carried out by a separate low frequency cycle, no restriction is placed on baseline test frequency.

Crack opening stress (S_{op}) measurements

The crack closure phenomenon[11] explains most load interaction effects observed in thin sheet materials under variable amplitude loading. Many FCP models use this mechanism to predict life under random service load spectra.[12,13] Crack closure under random loading is therefore of great significance in experimental studies. However, few studies[14,15] have been conducted to measure crack opening load in FCP tests under random loading. This could be due in part to the tedious nature of recording and interpreting compliance and other *data* to estimate crack opening load. To overcome this problem, a technique was developed for fully automated estimation of crack closure and crack opening load during FCP tests. It uses an iterative least square analysis algorithm which was developed earlier to analyse crack growth rate *data*.[16] The method is schematically described in Fig. 5. It requires application of a complete load cycle each time a measurement is to be carried out. This crack closing/opening load determination cycle is a slow downward ramp (0.5 Hz) starting from a load level at which the crack is certain to be open (maximum stress in case of a constant amplitude sequence). During this ramp, load and COD sampled every 10 ms are stored (a total of about 200 points). The downward excursion stops at zero load. A machine code routine then uses the algorithm in Fig. 5 to process data to determine the load level corresponding to crack closure. This is followed by an upward ramp, during and after which the same exercise is repeated to determine crack opening load level. The entire cycle takes about 2 seconds of real time (the time taken for the iterative least square analysis is a fraction of a second). The procedure includes logic to exclude obviously incorrect estimates; for example, the

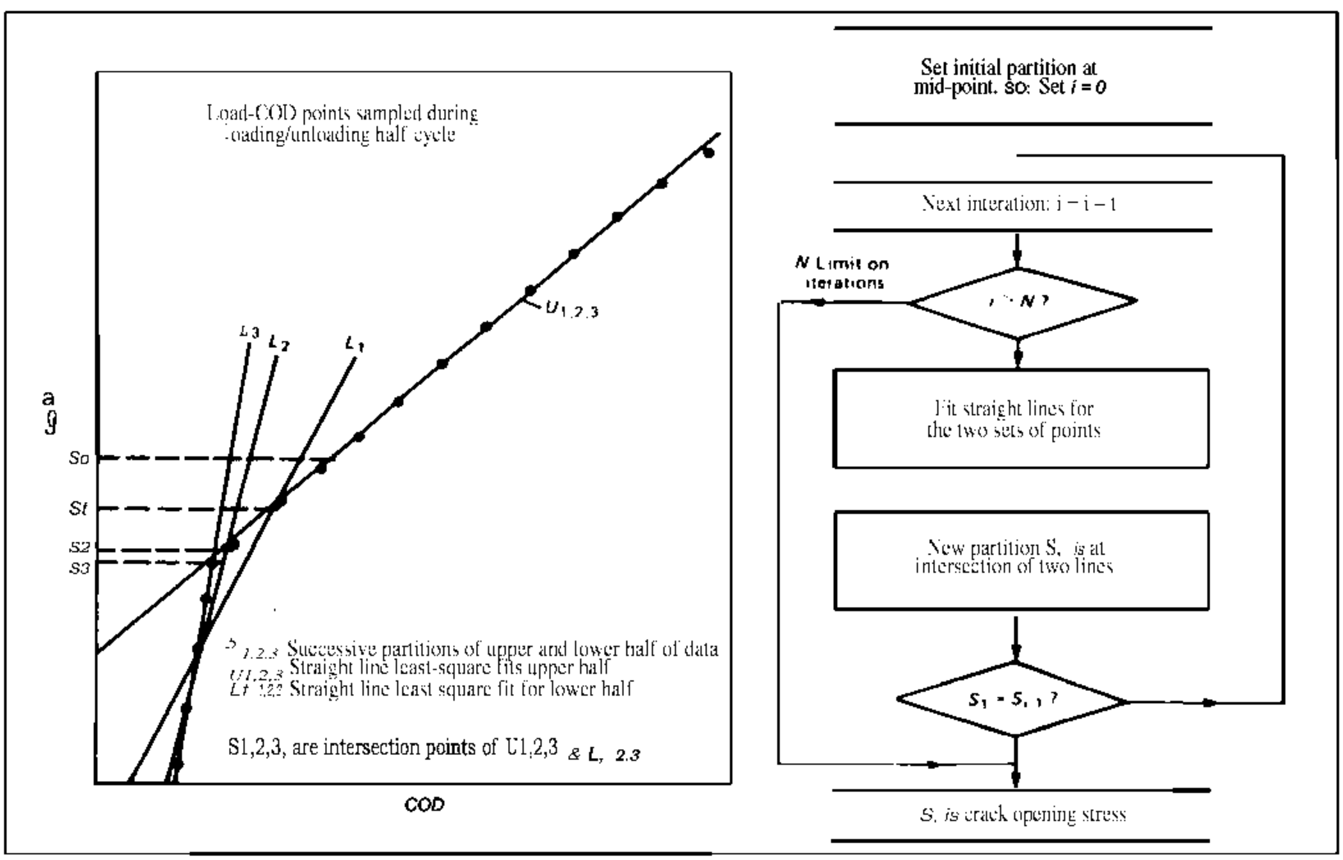

Fig. 5 Iterative technique for automated crack closure stress measurement

estimate is considered invalid if compliance does not increase with load.

At the conclusion of the test, crack opening and closing load levels are recorded alongside crack length and number of blocks in the table of test results. These form part of the FCP data bank file on disc storage. This feature permits a more meaningful analysis of test results. Under constant amplitude loading, crack closure data permit correlation of stress-ratio effects. Under spectrum loading, they provide a basis for explaining load interaction effects. Implementation of the proposed S_{op} determination technique appears to be an attractive prospect. It must be pointed out, however, that it has certain intrinsic limitations associated with the mounting of the gauge. As the crack grows away from the edge ($a > 15$ mm), the S_{op} estimates tend to become more and more unreliable as will be seen in data presented below. Further, the accuracy of the technique even at small crack lengths requires validation using other proven techniques. It is proposed to carry out such an exercise using the electron fractography technique proposed in Reference 17.

On-line fatigue cycle analysis

Consider the load spectrum in Table 1. Many load excursions occur below zero stress. Such load cycles obviously do not contribute to fatigue crack extension. The load spectrum contains a large number of small excursions ($0.5g$) which amounts to about 5% of the largest load cycle. At low mean stresses and small crack lengths (low mean stress intensity), such excursions possibly induce stress intensity ranges below the fatigue threshold. Attempts have been made[18] to evaluate criteria for load omission. However, these studies were carried out 'off-line' (prior to the test). This is permissible in crack initiation studies, where fatigue limit is the critical variable. In crack growth, K-threshold has to be taken into account. In view of the moving crack tip, this requires constant readjustment of omission levels.

With a high speed digital computer controlling the test, these factors can be considered 'on-line' during the process of test load sequence generation. Elimination of unnecessary load cycles can lead to considerable reduction in test duration without in any way affecting the test result. It should be noted, however, that identification of cycles to be deleted must be carried out on the basis of a suitable cycle counting technique. The matrix in Table 1 shows characteristics of load excursions, not of complete load cycles. These excursions may form part of other (larger) cycles. Therefore fatigue damage due to a particular load excursion cannot be directly estimated.

Fractographic evidence[19] suggests that the rainflow technique can be used to count complete load cycles for the FCP process from a random load sequence. Such an analysis was carried out for the load spectrum in Table 1. The results appear in Table 2 as frequency of occurrence of (closed) cycles with different combinations of peak and range. A number of features relevant to FCP emerge from Table 2.

Assuming that for a given crack length and load level $0.5g$ range falls below K-threshold, load cycles to the right of line EB will not contribute to the FCP process. With decreasing K-mean, this line will move to the left, encompassing larger g-ranges. Similarly, with increasing K-mean, it will move to the right as the smaller load cycles come above K-threshold. For sake of brevity it is assumed here that g-threshold is stress-ratio independent and EB is therefore a vertical line.

Assuming that under spectrum loading crack opening stress level is more or less constant (and equal here to $2.5g$), line AD is drawn to mark a boundary, the cycles above which cannot contribute to FCP (crack is fully closed). Line AC represents a boundary to the right of which fatigue cycles will be acting on a fully open crack tip. The elements immediately to the right of this line have minimum load

Table 2. Matrix of rainflow counted cycles from Table 1.

Peak \ Range (g)	12.0	11.5	11.0	10.5	10.0	9.5	9.0	8.5	8.0	7.5	7.0	6.5	6.0	5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	0.5
-2.5																								
-2.0																								2
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-1.0																						0	1	1
-0.5																					0	0	3	2
1.0																				0	1	0	2	8
0.5																			0	1	1	2	20	60
1.0																		3	27	40	22	39	472	2409
1.5																	4	11	24	19	41	322	3449	1773
2.0																3	16	10	14	19	115	1125	1398	564
2.5															0	16	10	2	7	80	555	580	529	336
3.0														0	3	11	3	4	64	381	312	207	324	196
3.5													0	10	6	0	8	38	268	196	74	116	194	140
4.0												0	2	7	2	5	24	179	120	34	35	55	116	75
4.5											1	0	1	1	0	17	126	79	12	19	29	44	76	43
5.0										0	0	3	0	4	16	92	52	6	10	10	15	23	44	26
5.5									0	0	1	0	3	11	64	27	8	2	3	4	6	10	23	9
6.0								0	1	0	0	0	5	57	19	2	3	5	3	3	4	7	10	4
6.5							0	0	0	0	0	5	32	13	2	1	0	1	2	2	1	4	5	1
7.0						0	1	1	0	0	6	14	8	1	1	1	1	1	2	0	2	3	2	2
7.5					0	0	2	0	0	2	10	5	1	0	0	0	0	1	0	0	0	0	2	2
8.0				1	1	0	0	0	2	6	1	0	0	0	0	0	0	0	0	0	0	0	0	0
8.5			0	0	0	0	0	3	4	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9.0		0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Range

equal to the assumed crack opening level (2.5g). The fatigue crack will be partially closed under the load cycles to the left of AC and below AD.

To summarize, there are four characteristic regions: 1) minimum load exceeds crack opening level, 2) minimum load falls below crack opening level, 3) maximum load is below crack opening level and 4) load range is below threshold for crack extension. This provides a convenient format for FCP analysis. The cycles in regions 3) and 4) can be deleted as they do not contribute directly to the FCP process. It must be noted, however, that the severe underloads in region 3) and overloads in region 4) can contribute indirectly to FCP, by affecting crack opening level for example. They therefore cannot be completely ignored.

All the features described above are incorporated in a computer procedure that was developed for on-line fatigue cycle analysis during FCP testing. Its flow-chart appears in Fig. 6. Peak-trough sequences are first generated and stored for the entire flight. They are then checked (and corrected if required) for proper peak-trough-peak sequencing. These are then subjected to rainflow cycle counting. Three conditions are examined as a basis to eliminate cycles from the load sequence to be applied on the specimen:

1) load range falling below specified omission level
2) stress intensity range falling below threshold value
3) maximum load falling below specified (crack opening) level.

Conditions 2) and 3) allow consideration of material properties. The first condition has been included to enable the study of overall load omission on the FCP process.

The consequences of carrying out on-line fatigue cycle analysis and elimination of counted load cycles are schematically described in Fig. 7. Note the dramatic reduction in the number of load cycles (particularly at low mean stress intensity) which leads to accelerated testing. The algorithm for rainflow analysis will always retain the highest and lowest loads in each flight, irrespective of the number of deleted cycles (*eg* 20, 33 in Fig. 7). Apart from the severest peak and trough, a few more half-cycles may remain uncounted depending on the precise load sequence in each flight (*eg* 10, 13, 34 in Fig. 7). Thus, irrespective of the assigned omission levels, at least the most severe peak and trough in each flight would continue to be applied on the test specimen. This ensures that load interaction effects due to extreme loads will continue to prevail.

Pseudo-random load generation and on-line fatigue cycle analysis are performed by a machine code routine. Using this program, the PDP 11/23 fatigue test controller is capable of controlling up to three independent spectrum loading FCP tests running at up to 25 Hz. Prior generation of load sequence and on-line fatigue cycles analysis results in a pause of about 100 ms between flights.

Experimental results

A series of constant amplitude and combat aircraft spectrum loading FCP tests were recently concluded in an effort to characterize 1 and 5 mm thick D16-AT alloy sheet material. This is a Soviet Al-Cu alloy similar in composition and properties to 2024-T3. 75 mm wide SENT specimens cut along the rolling direction ere used in the tests which were carried out on the computer-controlled test system.

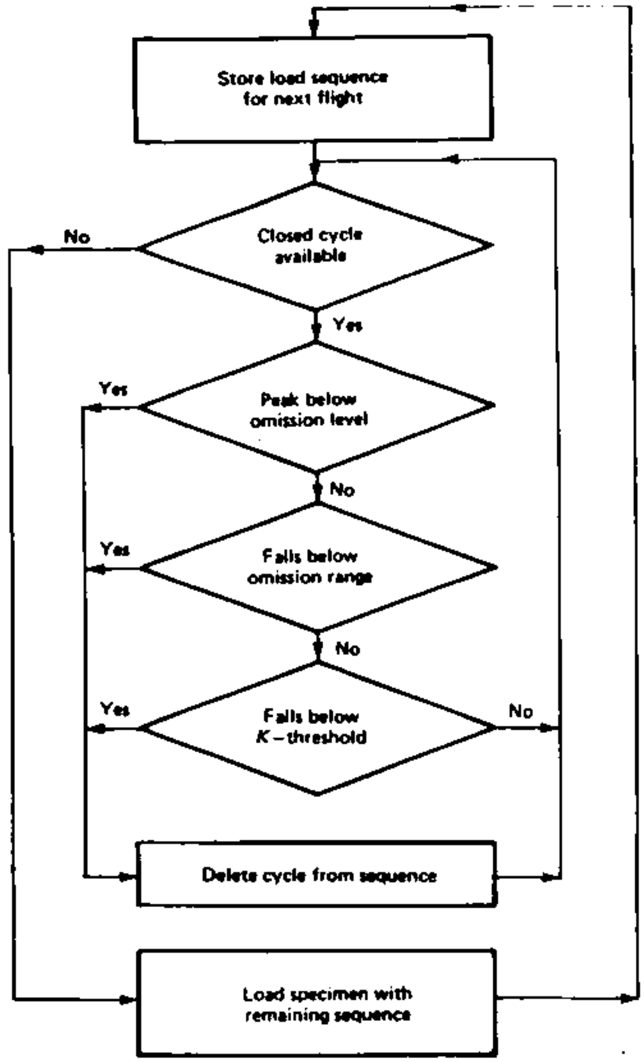

Fig. 6 Flow-chart for on-line fatigue cycle analysis

Some of the results from spectrum loading tests on the 5 mm thick material are described below. In these tests, the specimen was precracked to 5 mm length using a constant amplitude load sequence with maximum stress constituting 63% of spectrum truncation level.

FCP under stress and K-control

Tests were carried out at three constant mean (1g) stress levels and under different rates of linear variation in stress intensity (K-control). The results of these tests are described in detail in Reference 4. Fig. 8a shows da/dN curves for the various stress and K-controlled conditions. The K_m function for individual tests are also shown in the figure. The thin lines represent data for stress-controlled conditions (S_m = 15, 20 and 25 MPa). These are similar to conventional test results for spectrum loading and more or less fall into a single band as suggested in Reference 20. Under K-control, however, *da/dN* varies by more than an order of magnitude at a given K_m, depending on *dK/da*. Fig. 8b shows measured values of S_{op} during the K-controlled tests. Also included are S_{op} values under two constant amplitude tests with K_{max} variation similar to truncation load stress intensity during two of the spectrum load tests. (The truncation K_{max} for the spectrum load tests is nine times the K_m, hence the difference between K_m and K_{max} function constants.) The S_{op} values

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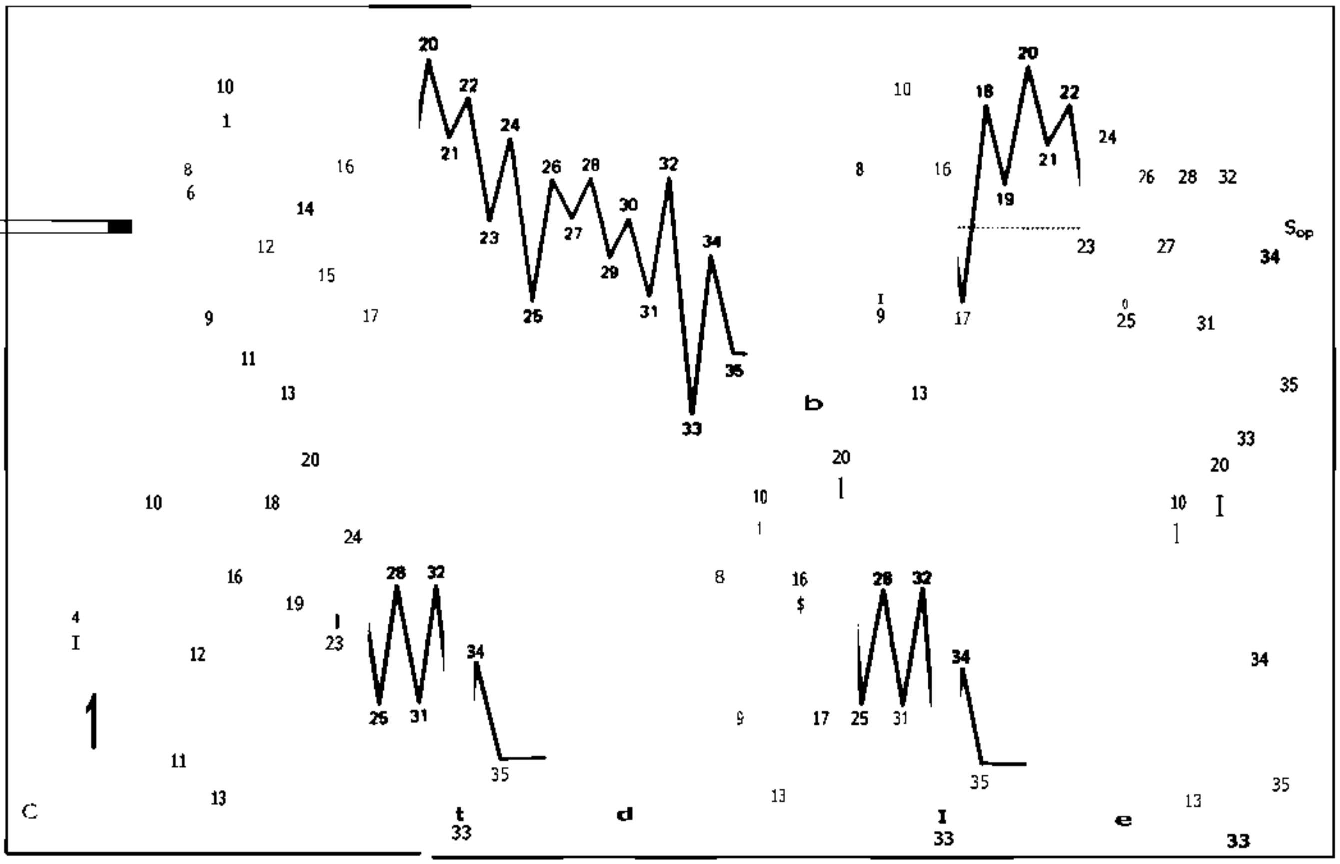

Fig. 7 Consequences of on-line fatigue cycle ar.alysis: (a) initial load sequence, (b) cycles below crack closure load omitted, (c), (d), (e) cycles of progressively larger range omitted - sequence . annot be further condensed

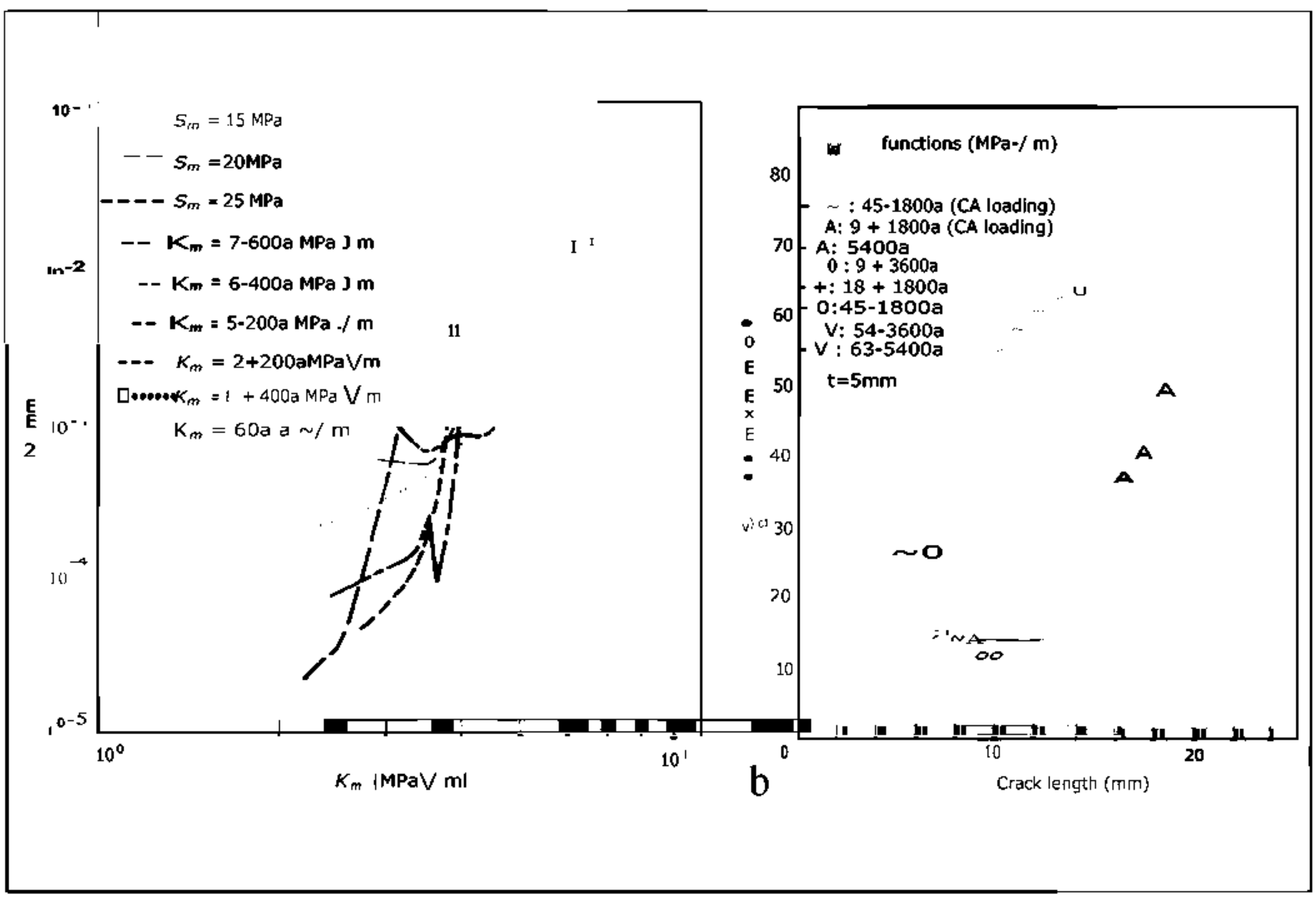

Fig. 8 (a) Spectrum loading crack growth rates and (b) crack opening stress under stress- and K-controlled loading show a fair degree of scatter, perhaps due mainly to the quality of the COD gauge and the procedure used for S_{op} measurement. Nevertheless, they appear to explain the trends in da/dN data observed in Fig. 8a. It follows from Fig. 8 that, under spectrum loading, da/dN strongly depends on dK/da and that variation in da/dN is closely related to variation in S_{op}. Obviously, dK/da effects under spectrum loading manifest themselves through S_{op}. This feature has been discussed in detail elsewhere. Apparently, S_{op} is affected by the rate of change of plastic zone size (K_{max}). Under spectrum loading, truncation level controls this parameter. Truncation level loads are extremely high (and rare). dK/da effects have not been noticed under constant amplitude loading because such high load levels are usually not used in tests (they are associated with da/dN exceeding 0.01 mm/cycle).

Effect of net stress

While a fatigue crack is open, crack closure effects would be controlled by stress intensity. Once the crack is closed, however, it is reasonable to expect that net stresses, including bearing stresses in the wake of the crack, become significant variables. It follows that, particularly under spectrum loading where periodic underloads are not uncommon, one can expect net stresses to influence the FCP process through crack closure.

Two experiments were conducted to investigate this possibility. In the first, two tests were conducted at identical dK/da but different offsets in the K-function. This ensured similarity in both K as well as dK/da but dissimilar crack length (and hence net stress) at any given K. The test results appear in Fig. 9.

The results of the second experiment appear in Fig. 10. In this experiment, an identical constant mean stress intensity was maintained in all the tests. The thin line represents results for a test using the full load spectrum (no loads omitted). The three thick lines represent results from tests with different levels of truncation of minimum load: these tests were conducted using a simplified load spectrum (one cycle per flight) to conserve test time. As expected, all the da/dN curves stabilize after some initial acceleration.

The data in Figs 9 and 10 are contradictory. The curves in Fig. 9 indicate reduced growth rates at lower net stress, given similar K and dK/da. The dK/da effect appears to diminish with increase in crack growth rate. On the other hand, the data in Fig. 10 point to a small but consistent increase in da/dN with crack length (at constant K, net stress decreases with crack length). The curve for the test with all compressive loads excluded

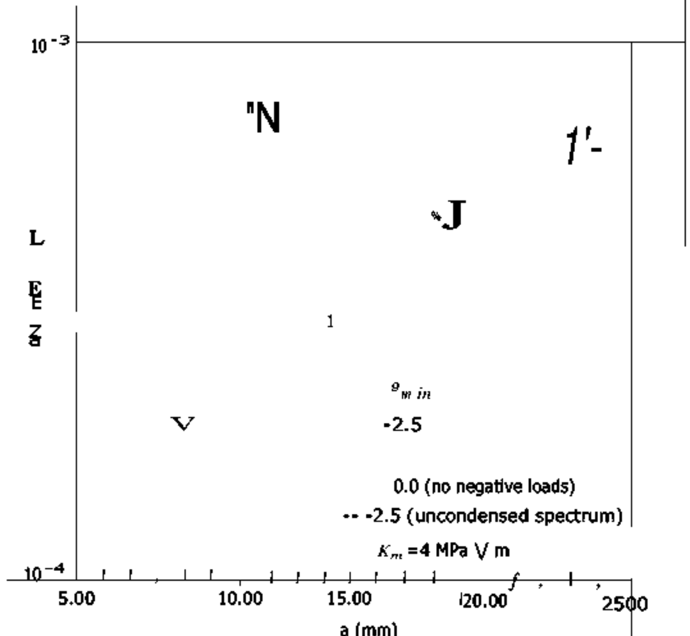

Fig. 10 Effect of minimum load truncation on da/dN under spectrum loading with K = constant

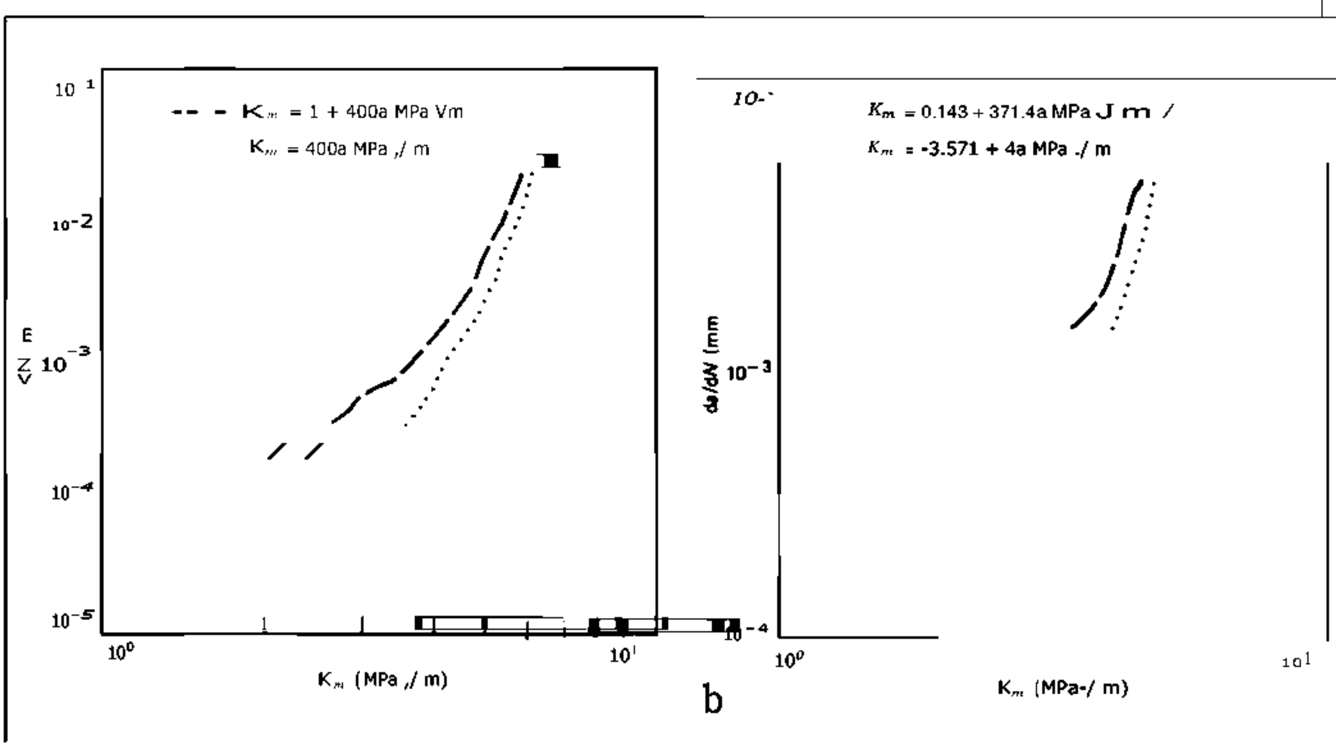

Fig. 9 Effect on da/dN of shift in K-function with same dK/da: (a) t = 5 mm, (b) t = 1 mm

shows the largest increase in da/dN with crack length (crack growth rate doubles with extension from 9 to 25 mm). Interestingly, all three curves merge with crack extension, possibly because compressive net stresses tend to zero. More systematic studies of net stress effects are required to draw any meaningful conclusions. At this stage one can only speculate on a strong interaction of K, dK/da and net stress (both tensile and compressive).

On-line load sequence modification

A few exploratory tests were carried out with on-line modification of the load sequence using rainflow cycle counting. These tests were conducted under K-control, with identical linear functions of decreasing K with crack length. For these tests, the load spectrum was truncated to 5g to enhance the contribution of smaller load cycles to the FCP process.

Omission of counted cycles occurring below given level

Four different omission levels were selected: 1, 1.5, 2 and 2.5g. Counted cycles with maximum load falling below this level were omitted. A fifth test was carried out with all counted cycles omitted (one or two cycles per flight). The test results appear in Fig. 11. The da/dN curves for the three lower omission levels fall into a single scatter band. It follows that crack opening level was close to 2g - omission of cycles below this level made no difference to the test results. However, test duration was reduced dramatically, almost by a factor of 10. Omission of cycles with maximum load above 2g resulted in a noticeable shift in the da/dN curve.

Omission of cycles below given K-range

Tests were conducted with three different 'threshold' K values (7, 10 and 15 MPa √m). Counted cycles with K-range falling below the specified threshold were omitted. To reduce test duration, an additional omission level of 2g (based on results in Fig. 11) was specified. The test results appear in Fig. 12. These results show a systematic effect of omission range. Obviously, at the given overall mean stress intensity, even the smallest (0.5g) load ranges contribute to the FCP process. Such load cycles could perhaps

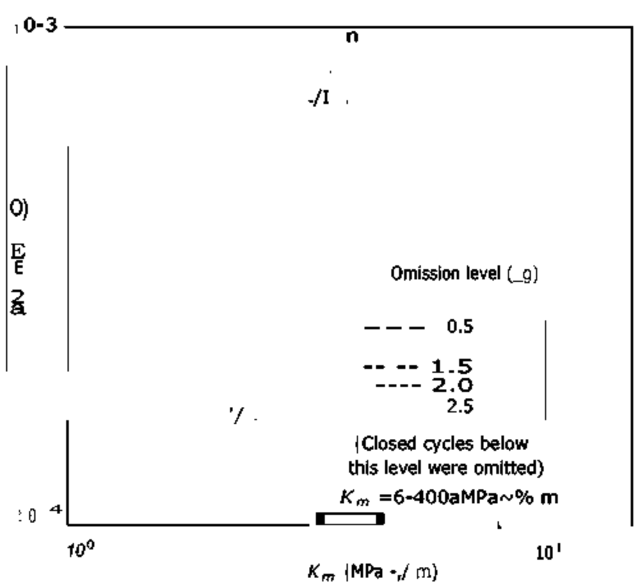

Fig. 11 Effect of omission level on *da/dN* under spectrum loading for D16AT alloy, t = 5 mm

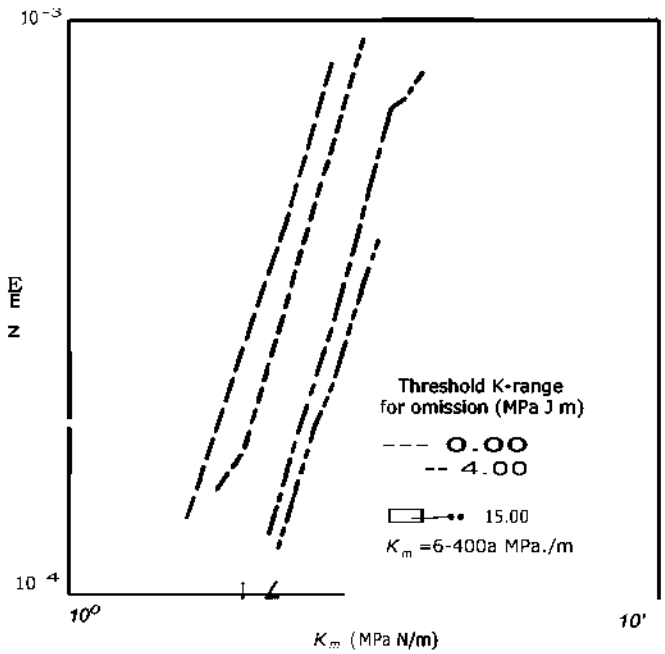

Fig. 12 Effect of omission range on da/dN under spectrum loading for D 16AT alloy, t = 5 mm

have been omitted had overall K-mean been less. At omission range of 15 MPa √m, most flights contained only one or two cycles. These last two suggest that only loads below S_{op} should be omitted, or at least 'threshold' K-range should be close to zero.

Concluding remarks

The results of exploratory tests described above show certain interesting features of FCP under spectrum loading:

- da/dN is dependent on dK/da - similarity in K_m alone is not adequate for similar da/dN
- net stress also affects da/dN, particularly when compressive stresses are involved
- on-line fatigue cycle analysis permits elimination of load cycles which do no affect the FCP process.

At the outset, it must be pointed out that conventional test procedures would not have permitted the kind of tests which revealed the above features. The last feature indicates the possibility of significant reduction in test duration without compromising results (provided prior information is available on threshold stress intensity and crack closure level). Fig. 13 shows how omission level affects flight duration. Alternatively, on-line fatigue cycle counting can be employed to determine empirically the 'effective' crack closure and threshold K.

The test system considerably widens the scope of FCP tests under spectrum loading. The experimental data obtained on it point to a requirement for serious consideration of standards to govern FCP tests under spectrum loading. Such standards should be primarily directed towards generation of laboratory test data representative of load spectra, crack geometry and stress levels of practical interest. Future work may also be directed towards development of techniques for more accurate estimates of crack opening stress level.

Attempts at standardizing random load FCP test procedures should consider the following problems in

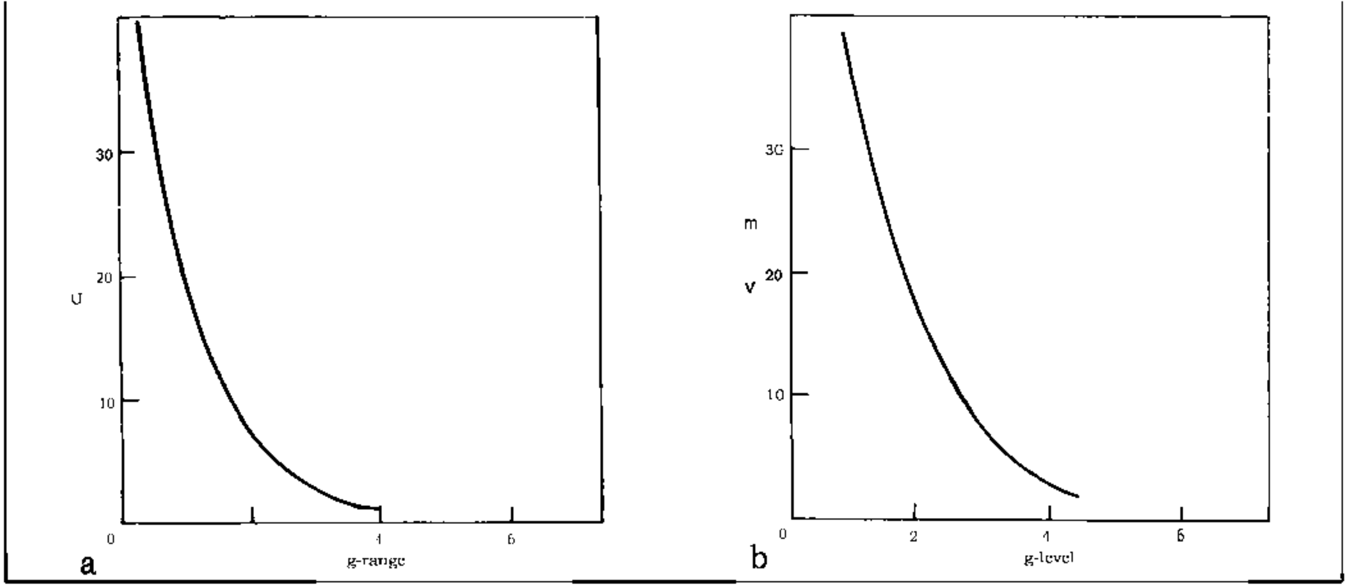

Fig. 13 Reduction in cycles per flight (test duration) with magnitude of loads omitted: (a) omission range, (b) omission level. (Data for spectrum in Table 1)

addition to those already identified[2] for constant amplitude tests:

- format for load spectrum representation and procedure for random load generation
- choice of stress/K control. Selection of mean stress level/K-function
- hardware and software for implementation of K-control. Procedures for independent control of tensile and compressive net stress
- on-line fatigue cycle analysis. Criteria for load cycle omission
- registration of crack closing/opening load levels, particularly in thin sheet materials
- signal conditioning to achieve required accuracy of random load sequences
- software for studies of the effect on FCP of major spectrum variables.

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